Proceedings of the 2006 IEEE
International Conference on Control Applications
Munich, Germany, October 4-6, 2006

An Experimental Comparison Study for Bilateral Internet-Based Teleoperation

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Abstract— **This paper presents a detailed experimental comparison of several published algorithms for motion and force control of bilateral internet teleoperators. Different control techniques based on wave variables, smith predictors, and recent algorithms on synchronization are compared under variable time delays, packet losses and environmental disturbances. The experiments are performed using a pair of two-link direct drive arms equipped with force/torque sensors and connected in a master-slave configuration. Comparing different control schemes on the same physical hardware allows a detailed comparison of their respective performance.**

I. INTRODUCTION

Over the last two decades, the rapid growing emphasis towards the extension of many telerobotics Internet-mediated systems has lead to a new set of communication and control challenges [1]. When the Internet is used as the communication channel in a telerobotic system, unavoidable time-varying delays, packet losses and disconnections may degrade the performance or even induce instability [2], [3]. Therefore, researchers have reported several control algorithms based on different techniques such as wave variables, compliance, wave predictors and synchronization in order to minimize the effect of transmission delays and data losses (the interested reader may consult [4]). However, this compilation of efforts available today in literature commonly disregards comparison data among algorithms.

Comparative studies among different control architectures are scarce in literature. A few studies have been performed assuming a communication channel with constant time delays and uninterrupted data rate [5]-[8]. Since these sorts of assumptions are not suitable for Internet communication, the present paper offers a comparative work with time varying delays and data losses. Taking into consideration time-varying delays and packet losses allows a meticulous comparison in the performance of different Internet-based control algorithms.

This work is organized as follows: A description of the experimental set up and the Internet model is given in Section II and III respectively. The implemented teleoperation schemes: force-position scattering transformation [9], digital data reconstruction [10], wave integral with filtering [11], [12], P and PD control [13], wave prediction with energy regulation [14] and, passivity based adaptive control [15] are highlighted and briefly discussed in Section IV. Results are presented in Section V followed by an introduction to a measure of complexity in Section VI. To conclude, Section VII offers a detailed discussion of the results and some final remarks.

This work was supported in part by the US Office of Naval Research Grant N000140510186 and by a SURGE Fellowship to the first author.

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II. EXPERIMENTAL SETUP

The experimental setup consists of two direct-drive two degree-of-freedom nonlinear robots coupled via a stochastic Internet model. The manipulators are made of aluminum and are actuated by two pairs of Compumotor Model DM1015-B brushless DC motors. Optical encoders are used to measure the position and velocity (by digital filters) of the links, while force-momentum sensors, located at the end-effectors, are used to measure the forces sensed/exerted by the operator/environment. For more information about the two manipulators, the reader can refer to [16].

The controllers and the stochastic Internet model are implemented using Wincon 3.3, which is a Windows application capable of running Simulink models in real time. The sampling time for the controllers and the communication channel is set to 4 ms. In addition, an aluminum wall is located at the slave side in order for the slave to make contact with it during the constrained motion experiment.

III. INTERNET MODEL

A stochastic network model is used as the communication channel between the two manipulators. The model implements a Markov chain that switches between different transmission conditions. Similar models using Markov chains have been broadly studied and used for network simulation [17], [18].

The advantage of a stochastic model is that enables the designer to specify the characteristics of the network to be simulated, such as the time delay and packet loss rate. In this study, four different Internet models were simulated in order to compare the performance of the control schemes under different time delays and packet loss rates. The stochastic characteristics for the forward (i.e. master to slave) and backward (i.e. slave to master) communications for the four experiments are shown in Table 1. The forward and backward transmissions are simulated independently from each other; hence, their characteristics are not necessarily the same. The achieved characteristics of Table 1 are comparable with the results reported in [19], where real data from several different Internet connections are surveyed.

TABLE I
CHARACTERISTICS OF THE INTERNET MODEL

Measures	Experiments			
	LD-A	HD-A	LD-B	HD-B
Minimum Time Delay (ms)	68	468	48	448
Maximum Time Delay (ms)	96	496	144	544
Mean Time Delay (ms)	80	480	80	480
Standard Deviation of Time Delay (ms)	3	3	22	22
Packet Loss Rate (%)	10-15	10-15	45-55	45-55

IV. TELEOPERATION ARCHITECTURES

In this section, some bilateral teleoperation control schemes are reviewed. Although it may not be exhausted, this selection nearly includes all the representative bilateral teleoperation schemes currently available in the literature.

A. Wave Scattering Transformation (WS)

The scattering transformation and passivity theory for teleoperation systems was originally developed by Anderson and Spong [9] and extended later to concepts of wave variables by Niemeyer and Slotine [20]. In this approach, wave variables are communicated via the delayed transmission lines, instead of power conjugated variables (i.e. force and velocity) as in many traditional bilateral systems. The use of the scattering or wave variable transformation guarantees passivity and the stability of the teleoperation system under any constant time delay.

B. Digital Data Reconstruction Filter (DD)

Under time-varying delay and packet loss, wave variables are distorted compromising the passivity of the system and leading to significant position errors [10]. To avoid the negative effects of distortion, Berestesky et al. proposed a novel solution based on the digital reconstruction of the wave variables [10]. Their approach introduces the use of a buffering and interpolation scheme that conserves the passivity of the system and improves the performance of the teleoperators under time-varying delays and packet losses. The main idea is to transmit the summation over time of the wave variable in sync with the current time. Doing so enables the receiving side to determine if the wave variable has been distorted and, consequently, to reconstruct the wave variable such that passivity and performance are enhanced.

C. Wave Integral and Reconstruction Filter (WI)

The original wave variable scattering transformation does not provide the teleoperators with explicit position information. Therefore, position tracking is not guaranteed. Niemeyer and Slotine proposed an original approach to solve this problem: transmitting the wave integrals [11], [12]. The wave integral encodes position and momentum information, thus explicitly providing the teleoperators with correct position feedback and preventing large tracking errors.

Although wave integrals assure a slave-to-master position tracking convergence, they do not ensure stability. Thus, Niemeyer and Slotine included a reconstruction filter in the design that guarantees a stable performance by preserving the passivity of the communication channel [11].

D. Proportional (P) and Proportional Derivative (PD) Control

In [13], Lee and Spong introduced the only teleoperation scheme in the comparison study not based on the wave scattering transformation theory. They proposed a Proportional-Derivative (PD) control scheme with damping compensation that guarantees the passivity of the closed loop teleoperator in the presence of parametric uncertainties and constant time delay, rather than passivity of the communication channel alone as in the scattering transformation theory. Even though their scheme does not guarantee stability of the system for time-variant delays, it is shown later in Section V that both control techniques (P and PD) remain stable.

E. Wave Prediction with Energy Regulation (WP)

In [14], Munir and Book introduced a control scheme for Internet teleoperation that predicts the incoming wave variable from the slave minimizing the negative effects of the transmission delays. Their scheme combines the use of the Smith Predictor and the Kalman filter to estimate the behavior of the slave and to compensate at the master side for delays and losses in the communication channel.

Since the predictor may generate more energy than what is coming into the communication channel from the slave side, stability may be compromised [14]. Hence, an energy regulator is used such that the system remains passive.

F. Passivity Based Adaptive Control (AC)

The last teleoperation architecture to be discussed is the passivity based adaptive control with wave scattering transformation, where the wave variables encode position, velocity and force information [15]. Chopra et al. re-designed the wave scattering transformation of [20] by incorporating a state feedback control law that guarantees passivity for any constant time delay, initial offsets and packet losses. Similarly to the wave scattering transformation and the P and PD schemes, no guarantee of stability under time-varying delay is given in [15]. However, experimental results (see Section V) show that the system is stable for the Internet models of Section III.

V. RESULTS

Two comparative studies were performed for each Internet model of Section III: free motion and constrained motion. The planned trajectories for the two studies are illustrated in Figures 1 and 2. A total of two repetitions were performed and averaged for all sets of experiments.

A. Comparison Criteria

Stability and performance constitutes the two main criteria in the comparison study. For stability it is meant that the system, under time-varying delays and packet losses, must have a human-environment *stable* and safe interaction, and achieve an equilibrium state when no forces are applied.

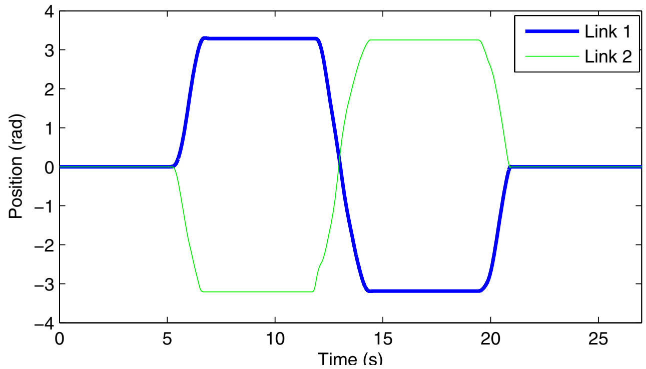

Fig. 1. Free Motion Trajectory.

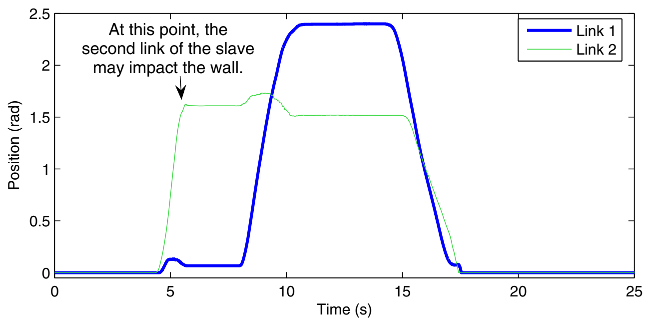

Fig. 2. Constrained Motion Trajectory.

By performance, some concepts are considered: 1) a low tracking error between master and slave in transient and steady-state conditions, 2) a faithful transmission of contact information (i.e. the operator should perceive the same net of forces applied to the slave at the remote side), 3) a low stiffness at the master side during free motion, and 4) a high stiffness during the constrained motion experiment.

In order to best satisfy the above criteria, a tradeoff between stability and performance was established when tuning the gains and parameters of each scheme. For instance, higher gains usually help to achieve smaller tracking errors and faster trajectory convergences. However, to do so require increasing the stiffness perceived at the master side and/or compromising the stability for some architectures, such as the P control [6]. Therefore, the gains were designed such that low tracking errors were achieved without imperiling the stability and limpness of the system.

B. Experimental Comparison: Free Motion

In this section, a comparative discussion between the wave scattering transformation (WS), the digital data reconstruction filter (DD), the wave integral and reconstruction filter (WI), the proportional (P) and proportional-derivative (PD) control, the wave predictor with energy regulation (WP), and the passivity based adaptive control with wave variables (AC) will be offered for the free motion experiment.

Figures 3 and 4 depict the tracking and steady state error respectively for all seven configurations using the Internet models of Section III. Some important observations can be listed based on the results:

- In general, higher delays render into larger transient and steady state errors.
- A higher packet loss rate does not affect significantly the response of the system for all the configurations except for the DD and WS schemes where the error is increased.
- The largest tracking errors during the transient response are obtained using the WS, P and PD architectures. The smallest tracking error is obtained using the WP control algorithm.
- In steady state conditions, the lowest position error for a small delay is achieved with the P scheme. For larger delays, the best results are achieved implementing the WI, WP and AC architectures.

C. Experimental Comparison: Constrained Motion

The next experiment evaluated was the performance of the WS, DD, P, PD, WI, WP and AC control schemes when the slave interacts with its environment. Figure 5 illustrates the response of all the teleoperation schemes in terms of the stiffness magnitude perceived by the operator at the master side and the difference between the forces sensed at both sides. Since a high stiffness emulates better the impact and contact of the slave with the wall, it is desirable for the human to perceive a higher stiffness during the constrained motion experiment indicating the presence of a wall at the remote side. It is also required for the teleoperation system to reflect the same net of forces at both sides giving the operator the sensation of having a direct interaction with

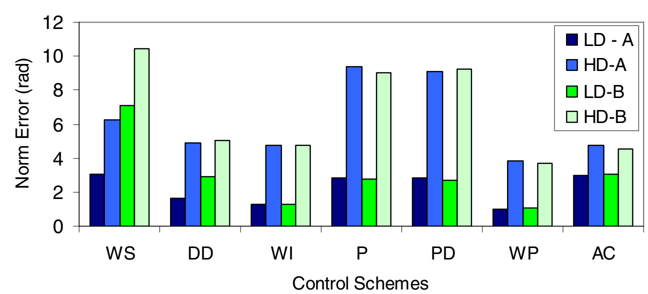

Fig. 3. Transient Error for the Free Motion Experiment.

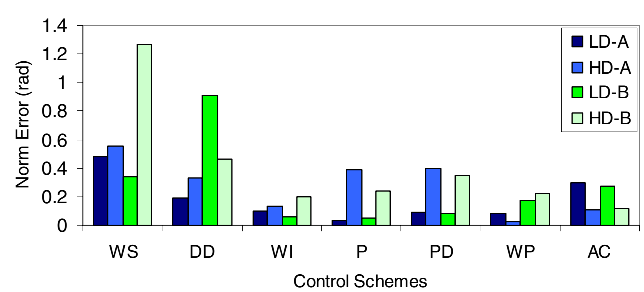

Fig. 4. Steady State Error for the Free Motion Experiment.

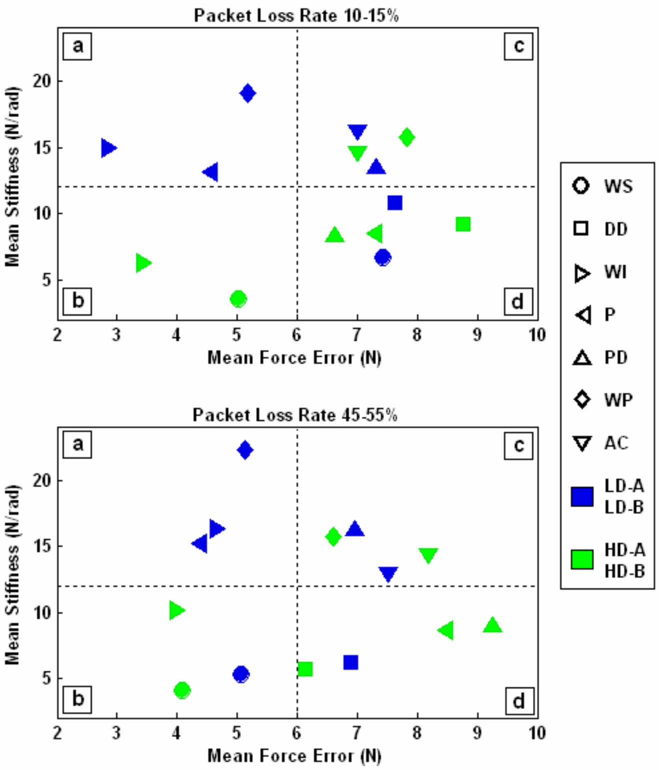

Fig. 5. Contact Information: Stiffness $\left(\frac{|F_{human}|}{|Position\ error|}\right)$ vs. Force Reflection Error ($|F_{human} - F_{environment}|$).

the remote environment. Consequently, it is preferable for all control schemes to lie inside quadrants *a* of Figure 5. The best results are then obtained implementing the WI, WP and P algorithms for small delays, and the WI, WP and AC architectures for larger delays. In contrast, the most unsatisfactory performances were exhibited by the DD and WS schemes.

Figure 6 depicts the steady state error for all configurations once the slave manipulator leaves the wall. The best results are attained using the AC scheme followed by the WI, P, PD and WP architectures. Notice that opposed to the free motion experiment, the steady state error for the WP scheme is increased. The reason lies on the fact that once the slave makes contact with the wall, the dynamic behavior of the system at the remote side is changed while the predictor's

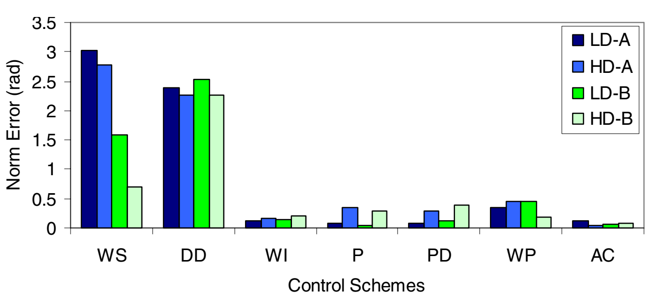

Fig. 6. Steady State Error for the Constrained Motion Experiment once the Slave Robot leaves the wall.

plant remains invariant. This mismatch between the real system and the predictor's estimate is the mainspring for the larger tracking and steady state errors.

VI. Measure of Complexity

Apart from stability and performance criteria, other considerations such as implementation, sensitivity and adaptability are of significant concern. How easy to design and implement is the control scheme? How easy is to adapt and modify the control algorithm in order to compensate for changes and uncertainties in the robot dynamics, task or workspace? An approach to answer these questions is to measure the complexity of the control schemes [21]. Intuitively, a simple control scheme should be easy to design, understand and modify.

In the following sections, a measure of complexity for the different Internet teleoperation schemes is given based on structural and computational complexity. It is argued that the combination of both measures appeals to the most common and general understanding on complexity.

A. Static Complexity

Static (or structural) complexity refers to how well the components of a system are connected [21]. Analyzing the connectivity patterns and understanding how well integrated are the components can provide information about adaptability and easiness of the design [22]. In this paper, a method called Polyhedral Dynamics is used to evaluate the structural complexity of the control schemes.

Polyhedral Dynamics, better known as Q-analysis, is an approach based on algebraic topology for studying the inherent structure of a system and the relationship of its components. It was originally developed by Ronald H. Atkin as a method to analyze the structural characteristics of social systems [22] and has been applied to other areas such as ecology [23], transportation [24], geography [25], communications [26] and project management [27]. Since a concise and excellent description of the Q-analysis can be found in [21], [25] and [28], a discussion of the method will be omitted. The results are illustrated in Table 2, where lager values indicate higher levels of complexity.

B. Computational Complexity

Another source of complexity is the amount of time and memory required by the computer to execute the control algorithm, which in computer science is known as computational complexity [29]. Traditionally, the runtime cost and memory size are estimated by counting the total number of operations and instructions of the algorithm [30]. Therefore, the time and memory space required by the control architecture can be estimated by measuring the code length of the control architecture.

When evaluating the computational complexity of the teleoperation control schemes, it is assumed that the control algorithms are irreducible in size. In addition, the measures are normalized in base of the shortest code such that the

TABLE II
MEASURE OF COMPLEXITY

Control Scheme	Structural Complexity	Computational Complexity
WS	2.97	1.00
DD	3.50	1.59
WI	4.10	1.16
P	2.67	1.00
PD	2.67	1.02
WP	5.07	1.20
AC	3.67	1.10

simplest algorithm has a unit value. The measures for the seven control configurations are given in Table 2.

The results on complexity illustrated in Table 2 coincide in general with the authors' opinion. The easiest algorithms to design and implement were the WS, P and PD architectures since they do not require additional programming and operations such as buffering, filtering or linearization. The most complicated and tedious algorithm was the WP scheme due to the involvement and design of numerous operations and parameters in addition to the need of an accurate mathematical model of the teleoperators' dynamics.

VII. DISCUSSION AND FINAL REMARKS

In this study, seven control architectures intended to improve the performance of internet bilateral teleoperators were tested and compared using two identical nonlinear robots in a master-slave configuration for different time-variant delays and data losses. The comparison criteria were based on stability, tracking error, transparency and complexity.

A. Stability

All seven control configurations proved experimentally to be stable for the Internet models of Section III. However, for the P, PD and WP architectures, higher gains and/or higher delays can easily lead the teleoperation system unstable. Consequently, stability's concerns impose a limitation in the gains' design.

B. Tracking Error

In general, the fastest response and lowest tracking error for transient behavior was obtained using the WP architecture. The slowest responses and larger transient errors were achieved using the WS, P and PD architectures. Under steady state conditions, the best results for small delays were achieved with the P scheme, while for larger delays the best results were attained with the AC, WP and WI schemes.

C. Telepresence: Contact Information

In the constrained motion experiment, the most faithful force reflection was achieved with the WI scheme and the highest stiffness value was measured with the WP followed by the AC architecture. The smallest steady state errors were attained using the AC and WI algorithms. In overall, the best responses were displayed by the WI and AC architectures.

D. Complexity

Based on structural and computational complexity, the WP scheme resulted as the most complex control algorithm. The less complex control schemes were the P, PD and WS algorithms.

E. Effects of the Delays and Data Losses

The experimental results evidence a proportional relation between the size of the delay and the magnitude of the transient and steady state errors for all seven configurations. In addition, the results suggest a robustness to different packet loss rates for the WI, P, PD, WP and AC schemes since the tracking and steady state errors did not vary significantly.

F. Final Remarks

Based on the results, it can be argued that the selection process of a particular control scheme is sensitive to the desired performance, task and/or characteristics of the communication channel. For instance, if a fast response and a low transient error is required by the particular task and no restriction is placed on the complexity of the control scheme, then the most likely choices are the WP, WI and AC techniques. In contrast, if the robot dynamics, tasks or workspaces are constantly changing, then the P and PD schemes may be preferred.

Furthermore, there exist other considerations which may influence the selection of a particular control scheme. For example, there may be the case in which the teleoperator dynamics is unknown. In this particular situation, the WP may not be an option since an accurate dynamic model of the system is required in the design of the control scheme. In addition, if enough information about the transmission delay is not available, the selection process favors the AC and WI schemes since all other control algorithms (except the WS scheme) require the designer to know an average, an approximate range and/or a maximum bound on the time delay.

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